KINETIK, Vol. 4, No. 1, February 2019, Pp. 75-86
ISSN : 2503-2259
E-ISSN : 2503-2267

Fuzzy Logic Control Design in Hybrid Energy Storage System Super-Capacitor Battery for Electric Vehicle

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Abstract

HESS is a suitable technology when applied to electric cars. One application is in SUV (Sport Utility Vehicle) car. The use of Supercapacitors can reduce the excess of load on the battery. Uneven soil contours cause current spike and drop in battery voltage which can reduce battery lifetime. This journal presents a simulated study of HESS batteries and Supercapacitors in SUV cars. Fuzzy-based energy management strategies and threshold control are introduced. The simulation study shows the difference between the control using the number of climb data and not, and the Fuzzy control response to the demand load. The simulation results mention the reduction of the maximum current and the battery voltage drop according to the load. The total energy ratio used between the two controls is also presented.

Keywords: *Fuzzy Logic Control, Hybrid Energy Storage, Supercapacitor, Battery Electric Vehicle, Energy Management Control*

1. Introduction

Hybrid Energy Storage System (HESS) is a technology that has huge potential advantages in the field of electric cars. The merger of two or more electrical energy storage devices with different and complementary characteristics is the essence of HESS technology. The batteries used in electric cars are the main energy storage components used to meet load demand alone. In practice, this can make the required battery capacity too large. In addition, the process of decreasing the ability of the battery during the charge/discharge process can reduce battery life. Supercapacitors emerge as complementary components of the storage device to cover the deficiencies of the battery [1]. Supercapacitor has large output power characteristic, the charge/discharge ratio is much larger than the battery, but the energy stored is slight.

One application of HESS is on the Sport Utility Vehicle (SUV). SUV car is a family car that is designed for the road with the up and down contours. Uneven road contours cause a spike of current and drop of voltage that can reduce the lifetime of the battery. The existence of uphill that more than one, causing the HESS system does not work properly. Supercapacitors are expected to help the performance of the battery that will be run out of energy when the car on first climb. There have been many previous studies on HESS with different control and optimization strategies, the use of adaptive fuzzy controls on HEV cars [2], wavelets-fuzzy in HEV cars [3], neural networks with dynamic programming optimization [1,4], fuzzy with Particle Swarm Optimization [5], and the use of SMC control [6]. Moreover, fuzzy for controlling electronic load control has been introduced by [7]. As intelligent control system, fuzzy has also employed for Fire-Extinguishing and Obstacle-Avoiding Hexapod Robot [8]. Previous HESS research has addressed the various problems that occur in each case, but not much discuss about the contours of the road in their research. Just a few for the research using road slope data [9].

In general, the use of Fuzzy Control methods on HESS there are two types, namely Fuzzy Mamdani and Fuzzy Sugeno. However, Fuzzy Sugeno is more suitable to apply to the HESS system, this is because Fuzzy Sugeno is able to be used well on loads that change non-linearly [10]. Fuzzy Sugeno method is a Fuzzy inference method for rules represented in the form IF - THEN, where the output (consequent) of the system is not a Fuzzy set, but rather a constant or a linear equation [11].

The purpose of this study is to design the HESS control strategy using batteries and Supercapacitors in FEV (full electric vehicle) SUV car, using a combined control between

Dhia, T., Mardiyah, N., & Nurhadi, N. (2018). Fuzzy Logic Control Design in Hybrid Energy Storage System Super-Capacitor Battery for Electric Vehicle. Kinetik: Game Technology, Information System, Computer Network, Computing, Electronics, and Control, 4(1). doi:http://dx.doi.org/10.22219/kinetik.v4i1.658
Receive June 07, 2018; Revise August 09, 2018; Accepted August 11, 2018

threshold control and fuzzy control Sugeno with the number of climb data used as input for control of energy management system.

2. Research Method

2.1 Data Retrieval

The route of the travel test is located in Batu, Malang district shown in Figure 1. Data collection starts from start point with coordinates -7.864308, 112.504536 to end point with coordinates -7.859131, 112.487075 '. Distance from start point to end as far as 3.974 Km.

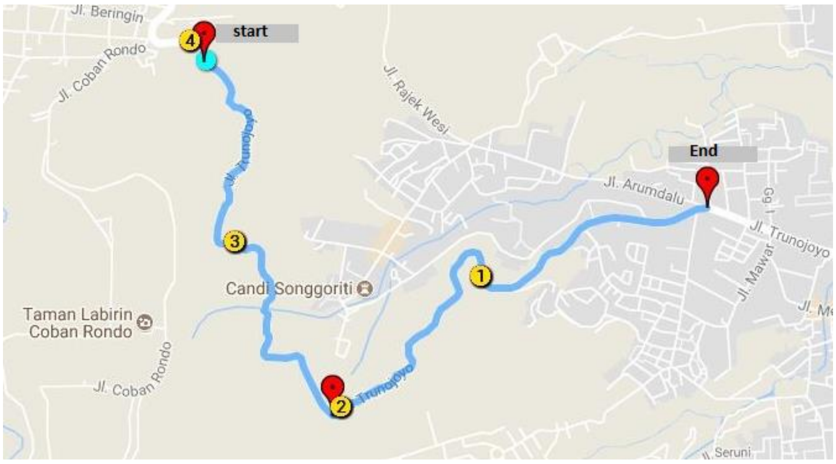


Figure 1. Route of Data Retrieval

The data obtained by measuring the altitude and speed of the vehicle directly on a predetermined route, the data obtained as shown in Figure 2. The object of the vehicle used is SUV type car (Daihatsu Terios) with two passengers (135 kg). Data collection is done by utilizing accelerometer sensor and GPS feature (Global Positioning System) on smartphone and supporting application "SpeedLogger" as user view. The data displayed by the application is the height of the road, and the speed of the vehicle with 1 second sampling.

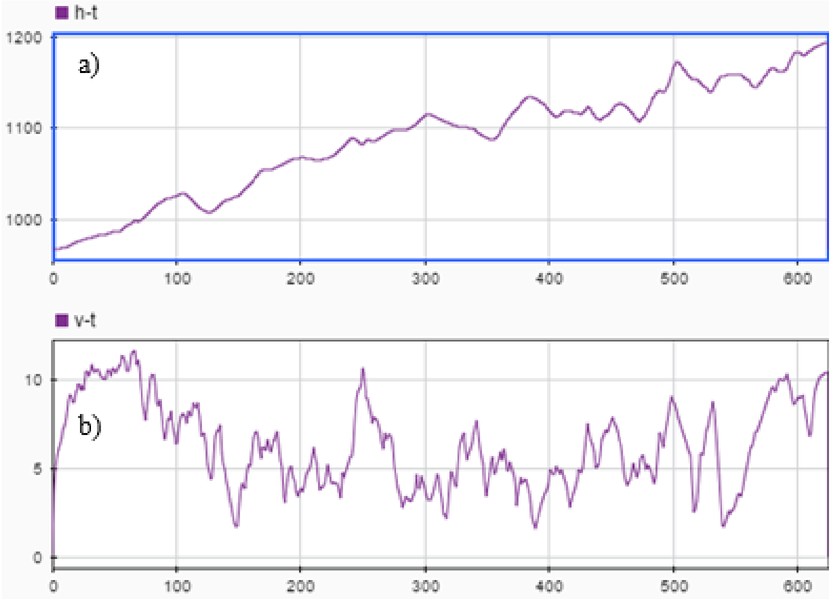


Figure 2. Measurement Graphs, a) Street Altitude Graph, b) Driving Cycle Graph

2.2 Power Demand Modelling

Modeling is done by entering the velocity and altitude data in Equation 1, 2, and 3 [12], and several other constants as shown in Table 1, resulting in demand power graphs as shown in Figure 3.

$$P_T = F_T.v \tag{1}$$

where F_T:

$$F_T = F_m + F_r + F_d + F_g \tag{2}$$

$$= m_v.a + C_r.m_v.g.cos(\theta) + \frac{1}{2}.\rho.v^2.A.C_d + m_v.g.sin(\theta) \tag{3}$$

Table 1. Variable of Power Demand

Parameter	Value
Weight vehicle and passengers (m)	1300 Kg
Wheel friction coefficient (C_r)	0,009
Gravity acceleration (g)	9,81 m/s^2
Air density (ρ)	1,2 Kg/m^3
Air friction coefficient (C_d)	0,45 Ns/m^2
Air crash area (A)	2.45 m^2

Figure 3. Power Demand Graph

2.3 Processing of Climb Counting Data

The number of climb data is obtained from the speed and altitude data that obtained from the data retrieval. The data conversion path shown in Figure 4. Changing the v-t data to s-t is done by integrating v-t data. h-s data can be formed by combining s-t data with h-t data. The algorithm in Figure 5 is used to obtain the graph n-s from the h-s graph, the new data can be used by converting the n-s into n-t data with the aggregation of time data, so the final result is the data n-t that seen in Figure 6. The concept of the number of climbs is shown in Figure 7, red circle indicates a rise in the route of the vehicle, and 'data out' is the output data system calculation of the number of climbs.

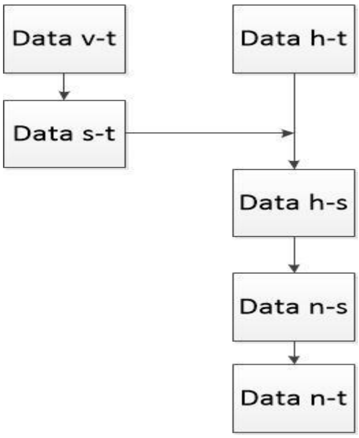


Figure 4. Input Data Conversion Path

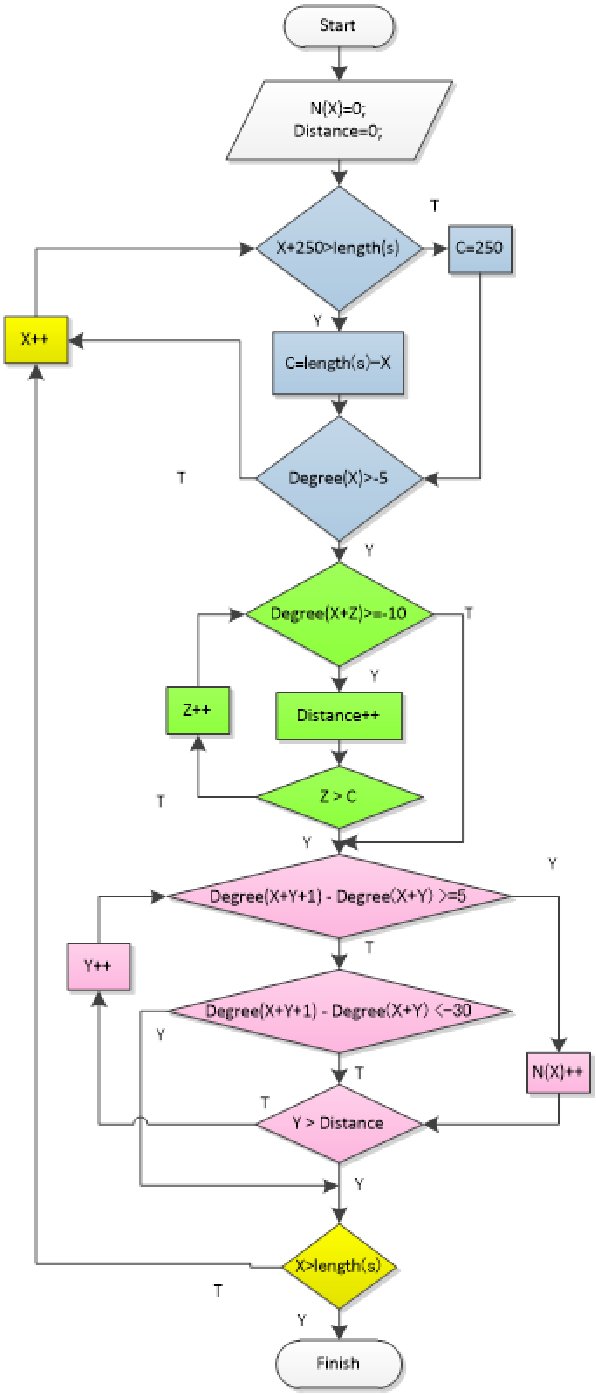


Figure 5. Algorithm of Climb Counter

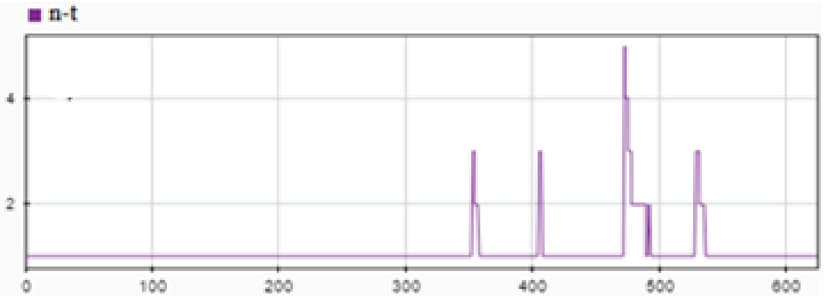


Figure 6. Climb Graph

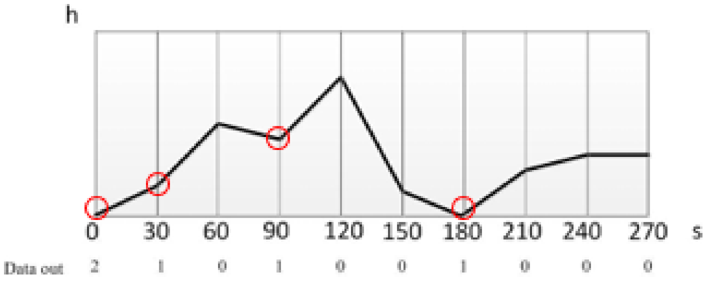


Figure 7. Sample of Climb Counter

The calculation algorithm of the number of climbs consists of 3 major parts in the processing of data. The parts of the algorithm will be marked with the color. In Figure 6 of the first section, the blue chart, an algorithm that use to select whether the data is included from the 250-meter data to the fore, and selecting the input whether the data is not a descend road, with -5 degrees value. The second part, the green-colored chart, use to determine whether the next 250 meters of data does not exist descend with -10 degree value. The third part, red chart, use to determine the number of climb by looking at the difference of degree from degree (i) to degree (i + 1), with value 5 degree, but if there is a difference far below -30 degrees then the program will automatically skip the process iteration. Another yellow chart only serves as a limit on the amount of incoming data.

2.4 System Structure

The whole system can be seen in Figure 8, where the battery is the main energy source, and the Supercapacitor is an additional energy storage device. Both the battery and the Supercapacitor are connected to DC-Link with a voltage of 310.2V through a bi-directional DC / DC converter, which can operate in both buck and boost mode. So that demand power can be fulfilled by supplied power from battery and Supercapacitor. In order to ensure the demand power by its supplier with good power dynamics, the energy control of the Fuzzy system is proposed in this journal, in order to fulfill the electric car demand power. The demand power of the Supercapacitor is the output signal of the EMS-FLC control, which is appropriate with the demand power, and the SOC of the Supercapacitor itself.

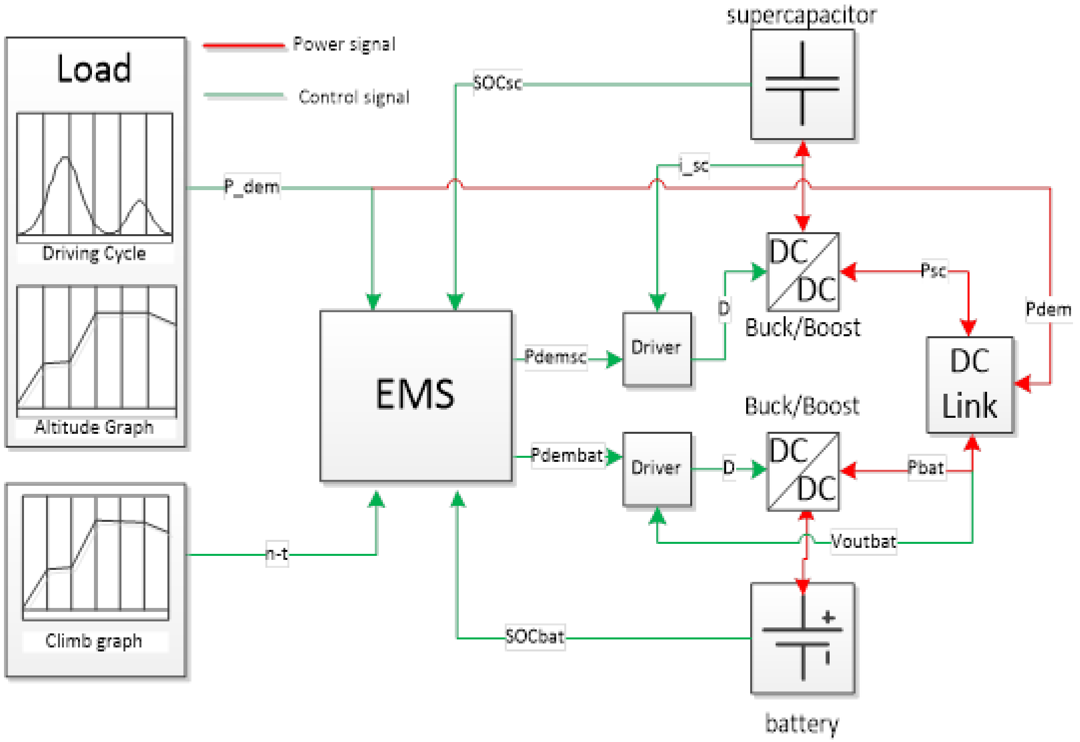


Figure 8. Full Block of HESS

2.4.1 Initialization of Component

The parameter of the inductor, capacitor and energy storage devices is shown in Table 2.

Table 2. Component Initialization

Component	Value
Capacity/ voltage/ internal resistance of battery	11 Ah / 240 V/ 218 mΩ
Capacitance/voltage/ internal resistance of Supercapacitor	29 F / 192 V / 8.9 mΩ
Inductance of Battery Converter	3.72 mH
Inductance of Supercapacitor Converter	15.9 mH
Capacitance of Capacitor at Converter Input side	362 mH
Capacitance of Capacitor at Converter Output side	260 mH
Capacitance of battery filter	1 F
Capacitance of DC-Link capacitor	1 mF
Resistance of internal IGBT	1 mΩ
Switching frequency	1000 Hz

2.4.2 Converter Driver

Processing of battery demand power control signal and Supercapacitor demand signal is different. Seen in Figure 9, battery-converter driver aims to keep the voltage at DC-Link constant that marked by the reference voltage input in the converter driver. Whereas in Figure 10 the superkapasitor converter driver uses the superkapasitor input current as a reference in order to meet the demand power.

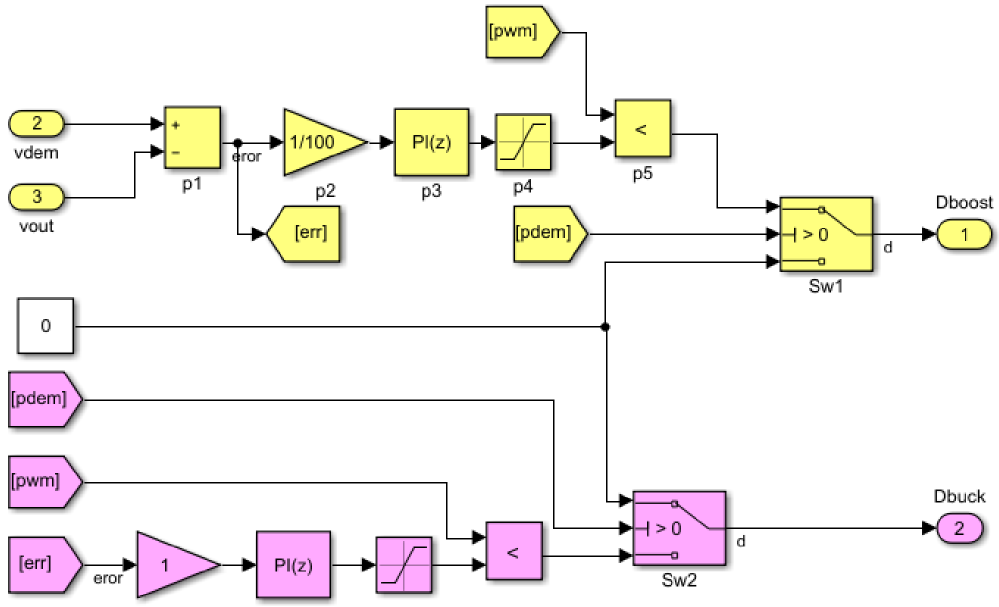


Figure 9. Driver Converter Battery Block

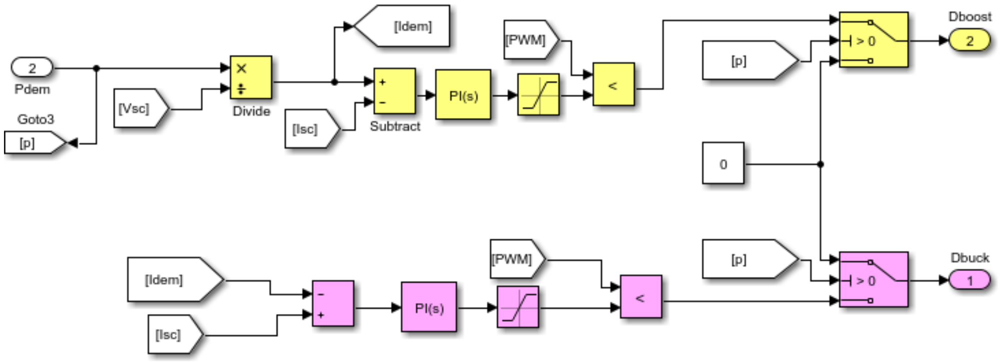


Figure 10. Driver Converter Supercapacitor Block

2.4.2 EMS Control Strategy

The EMS control consists of two parts, namely the SOC control of the battery and the FLC. The SOC controls batteries use conventional threshold controls. The SOC control of the battery serves to protect the battery so that the battery used is not excessive during discharge, so the battery will be cut-off when the SOC from the battery decreases to the specified, while the SOC limit is 30%. The block diagram looks like Figure 11, where the yellow blocks aim to protect the battery capacity, and stop the Supercapacitor supply.

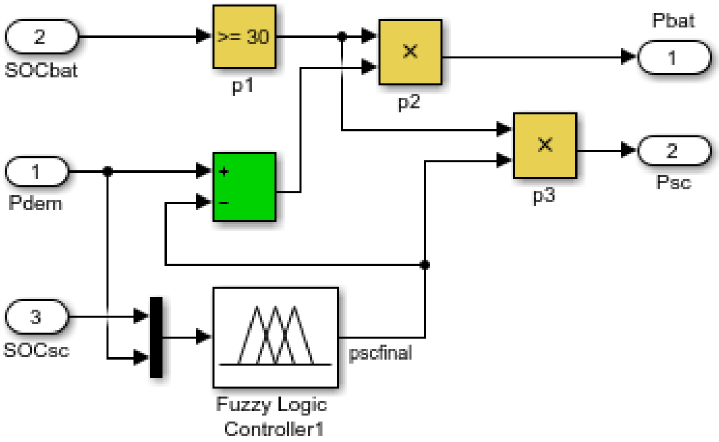
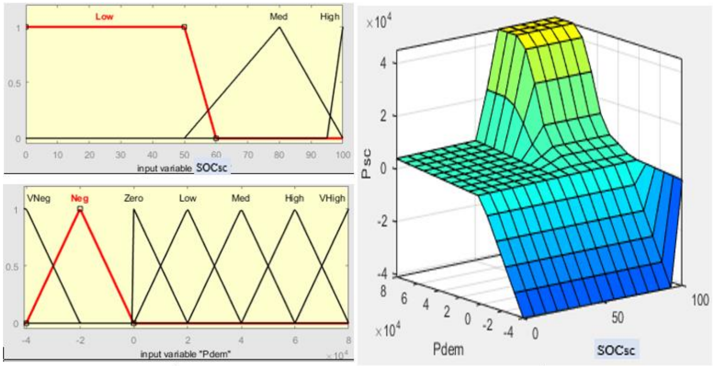


Figure 11. EMS Control Block

The FLC control regulates the power to be supplied by the Supercapacitor. This control is determined based on the SOC limit of the Supercapsitor, consider the maximum power output of the Super Capacitor and the battery, as well as the intuition and experience of the researcher. The Fuzzy Sugeno proposed using 2 inputs are SOC_{sc} and P_{dem}, and an output is Pdemsc or supercapasitor reference power, with membership function shown in Figure 12a. Parameters of membership function in Fuzzy Sugeno Control output as follows Equation 4.

$$
\begin{aligned}
Z_{Regen} &= y \\
Z_{Zero} &= 10_x + 0.05_y \\
Z_{Low} &= 0.25_y \\
Z_{Med} &= 0.9_x - 18000 \\
Z_{High} &= 45000
\end{aligned}
\tag{4}
$$

From the application of parameters that have been described above in 'Fuzzy Logic Designer Toolbox', then obtained the output as in Figure 12b.



a. b.

Figure 12. FLC, (a) Membership Function Input (b) Surface Graph of Input-Output Relationship

The Fuzzy Control rules applied to the control are shown in Table 3. The 'V' on 'VNeg' and 'Vhigh' means 'Very', whereas Regen in the output variable means ‘Regeneration’.

Table 3. Fuzzy Control Rule

Psc		P_{dem}						
		VNeg	Neg	Zero	Low	Med	High	Vhigh
SOCsc	Low	Regen	Regen	Zero	Zero	Zero	Zero	Zero
	Med	Regen	Regen	Zero	Low	Med	High	High
	High	Zero	Zero	Zero	Low	Med	High	High

3. Result of Simulation and Discussion

In testing the performance of the proposed control. Simulation study applied to Simulink Matlab. Battery model and Supercapacitor is an existing model in the Matlab library. In the EMS control simulation for HESS on driving cycle and road height graph, the SOC of the battery is set to full state (SOCbat = 90%), while the SOCsc Supercapacitor is half of its full capacity (SOCsc = 50%).

In the first simulation shown in Figure 13, the demand power graph is satisfied by the converter output power, and the average converter efficiency is 92.3%. Battery output power and Supercapacitor still undergo a transient process for 0.4 seconds on demand power.

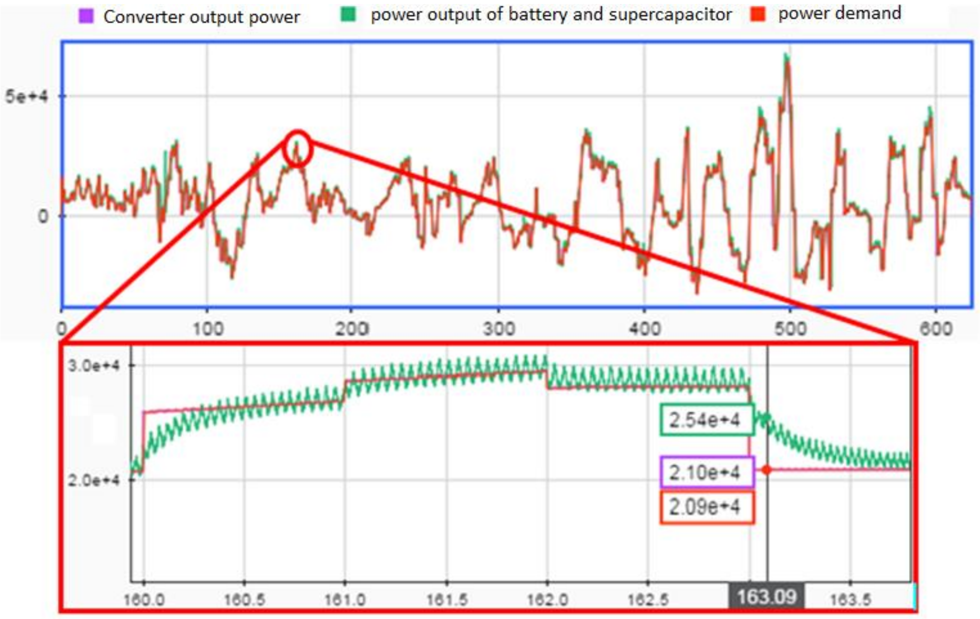


Figure 13. Response of Battery Energy/Supercapacitor to Energy Demand

The power distribution between the battery and the Supercapacitor against the demand power that was previously obtained is shown in Figure 14, the battery power output is flatter and decreased.

Figure 15 shows that the DC-Link voltage looks constant with a value of 310.2V, but there is still a voltage ripple generated, this causes the voltage 310.2 V DC-Link can change with the range 270-350V.

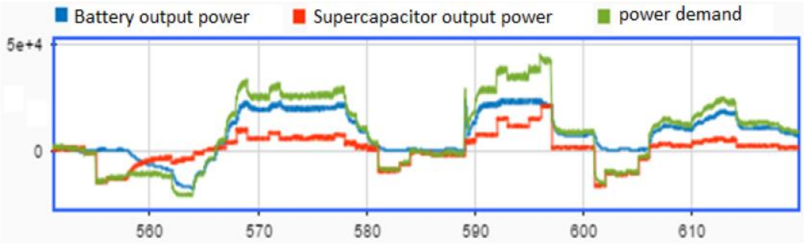


Figure 14. Simulation Result of Power Demand and Power of Battery/Supercapacitor

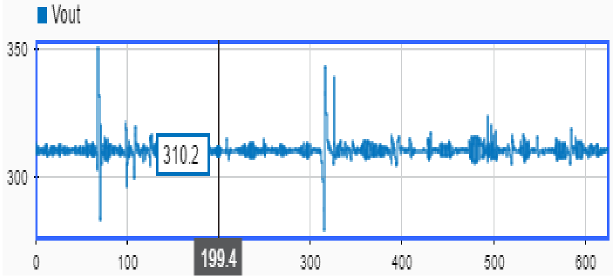


Figure 15. Simulation Result of DC-Link Voltage

The second simulation is performed by comparing the current and voltage response of the battery between two different controls. First use the climb counter data, and the second one does not use. There is a difference between the two controls in Figure 16a at point 482.9, the maximum current from the battery output using the climb data is 137.6A, while for the control without the climb data, the battery current is 92.8A. The battery control current without the climb data in Figure 16a is smaller than the battery current with the climb data, this is because of the climb data seen in Figure 16d is 2. Thus the supply power of the Supercapacitor between the controls with the climb data or control without the climb data seen on Figure 16b shows the output power of the Supercapacitor with a climb data is ½ times from the control without climb data, this causes the battery power supply of Figure 16c at the point 482.9 larger than the system using the climb data.

At point 501.9 in Figure 16a, the output current of the battery in the control system using the climb data is smaller than the non-use control, with the respective values of 81.5A and 221.4A. this indicates the presence of energy stored at point 501.9 in the Supercapacitor on a control system using climb data is higher than no-use. The climb data causes the Supercapacitor to be adjustable output according to the soil contour. Seen at point 482.9, where the Supercapacitor output is limited by the number of climb data.

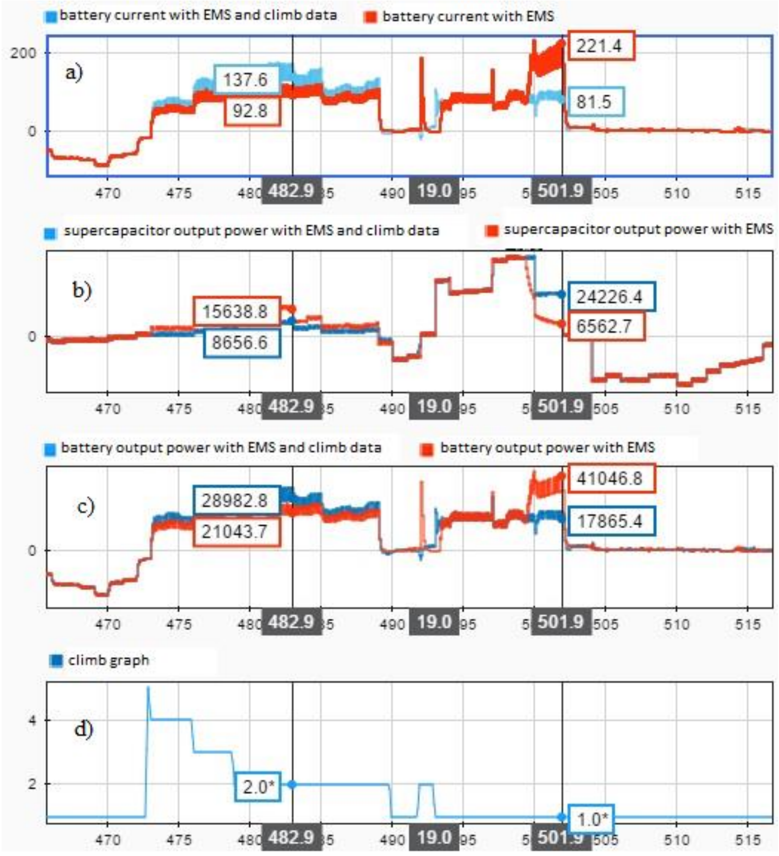


Figure 16. Battery and Supercapacitor Response to Numbers of Climb, (a) Battery Current, (b) Output Power of Supercapacitor, (c) Output Power of Battery, (d) Number of Climb Graph

The simulation result of the voltage response is shown in Figure 17, which shows the voltage drop that occurs in the battery when there is a large power demand that causes the battery output current is also large, shown in Figure 16a. At data point 482.9 Figure 17, It shows the battery voltage drop in the data not-using the number of climb is smaller than using the number of climb data, with 226.8V and 210.6V respectively, whereas at point 501.9 the voltage drop on the control without the data of climb seen more greater than that using the climb data with a value of 185.4V and 219.2V respectively, this corresponds to the load current required.

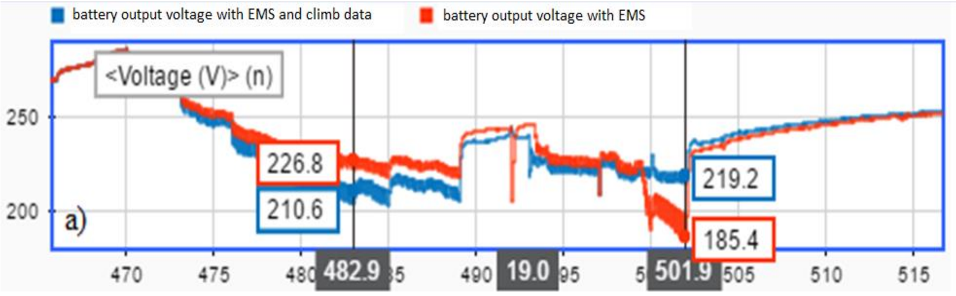


Figure 17. Battery Voltage Response

Table 4 shows the comparative results between the HESS controls using the number of climb data and not-using.

Table 4.Simulation Result of Control with Number of Climb and Not

Parameter	EMS	EMS + n-climb	%
Output Energy Total of Battery (MJ)	4,075	4,081	(+)0.14
Average Current of Battery (A)	28.19	28.37	(+)0.64
Maximum of Drop Voltage (V)	185,4	210,6	(-)13.6
Maximum of Current (A)	221.4	137.6	(-)37.9

The total energy output of the battery from the HESS system using the climb data will increase by 0.14%. The average current of battery output will also rise by 0.64%. The voltage drop on the HESS system using the climb data will decrease by 13.6%, and the maximum output current from the battery will decrease by 37.9%.

4. Conclusion

The EMS control for HESS designed in this report consists of battery protection controls using threshold controls, and Fuzzy controls. The Fuzzy control is formed by 2 inputs and 1 output, with inputs of request power and SOC of Supercapacitor, then the output is demand power for Supercapacitor, each of which has consecutive membership functions 3, 7, 5. Simulation results show that the battery output energy indeed reduced in the EMS control with additional input in the form of climb data, but the change is very small and can be ignored. On the other hand, a very significant change is seen in the peak battery current and the recorded voltage drop in the simulation is reduced drastically.

Notations

P_{demsc} = Power demand for Supercapacitor
P_{dembat} = Power demand for battery
P_{bat} = Battery output power
P_{sc} = Supercapacitor output power
SOC_{bat} = State-of-charge/ battery capacity
SOC_{sc} = State-of-charge/ Supercapacitor capacity
P_{dem} = Power demand
n-t = Data relationship between the number of climb with time
n-s = Data relationship between the number of climb with mileage
v-t = Data relationship between speed with time
h-t = Data relationship between the height of the road with time
h-s = Data relationship between the height of the road to with mileage

i_sc = Supercapitor's Flow Current
voutbat = Battery output voltage
D = Duty Cycle
F_T = total force
V = Speed of vehicle
F_m = Mechanical force
F_r = Wheel swipe force
F_d = Angle friction force
F_g = Gravity force
m_v = Mass car
a = Acceleration of the car
g = Acceleration of gravity
C_r = Coefficient of tire friction
C_d = Air friction coefficient
A = Area of air swipe
P = Air density
Θ = slope of the road
EMS = Energy Management System
HESS = Hybrid Energy Storage System
SUV = Sport Utility Vehicle
FEV = Full Electric Vehicle
FLC = Fuzzy Logic Control

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